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REGULAR ARTICLE

Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management

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Abstract Traditionally, crop production in sub-Saharan Africa (SSA) depends primarily on mining soil nutrients. Integrated Soil Fertility Management (ISFM) is an approach for intensifying agriculture in SSA that aims at maximizing the agronomic efficiency (AE) of applied nutrient inputs. ISFM contains the following essential components: proper fertilizer management, use of improved varieties, the combined application of organic inputs and fertilizer, and adaptation of input application rates to within-farm soil fertility gradients where these are important. This paper evaluates, through meta-analysis, the impact of these components on the AE of fertilizer N (N-AE), defined as extra grain yield per kg fertilizer N applied, in maize-based systems in SSA. Since N-AE is low for excessive fertilizer N application rates or when fertilizer is applied on fertile, unresponsive soil, as was confirmed by scatter plots against control yields and fertilizer N application rates, such values were removed from the database in order to focus on and elucidate the more variable and complex responses under less than ideal conditions typical for SSA. Compared with local varieties, the use of hybrid maize varieties significantly increased N-AE values (17 and 26 kg (kg N)$^{-1}$, respectively) with no differences observed between local and improved, open-pollinated varieties. Mixing fertilizer with manure or compost resulted in the highest N-AE values [36 kg (kg N)$^{-1}$] while organic inputs of medium quality also showed significantly higher N-AE values compared with the sole fertilizer treatment but only at low organic input application rates (40 and 23 kg (kg N)$^{-1}$, respectively). High quality organic inputs (Class I) and those with a high C-to-N ratio (Class III) or high lignin content (Class IV) did not affect N-AE values in comparison with the sole fertilizer treatment. Application of N fertilizer on infields resulted in significantly higher N-AE values [31 kg (kg N)$^{-1}$] compared with the outfields [17 kg (kg N)$^{-1}$]. The obtained information indicates that N-AE is amenable to improved management practices and that the various components embedded in the ISFM definition result in improvements in N-AE.

Keywords Improved maize germplasm · Meta-analysis · Organic-mineral applications · Site-specific nutrient management · Soil fertility gradients

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Introduction

The need for intensification of agriculture in sub-Saharan Africa (SSA) has recently gained support, in part because of the growing recognition that enhanced farm productivity is a major entry point to break the vicious cycle underlying rural poverty. Recent events include the launching of the Alliance for a Green Revolution in Africa (AGRA), which aims at increasing fertilizer use from the current 8 kg to 50 kg fertilizer nutrients ha^{-1} (Abuja Fertilizer Summit 2006), thereby acknowledging that sustainable intensification needs to rely on the sensible use of external nutrient sources. Since fertilizer is an expensive commodity and because the overuse of fertilizer can lead to undesirable environmental side-effects, Integrated Soil Fertility Management (ISFM) has been increasingly adopted by the research and development community as a framework for boosting crop productivity with minimal environmental impacts. Integrated Soil Fertility Management was recently defined as 'A set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles' (Vanlauwe et al., 2010).

The ISFM definition includes a number of concepts, including use of fertilizer and improved germplasm, combined application of fertilizer and organic inputs, adaptation to local conditions, and rehabilitation of degraded soils (Fig. 1). In terms of response to fertilizer, two types of soil are distinguished: (i) soils in which crop productivity responds to fertilizer – 'responsive soils'– (Path A, Fig. 1) and (ii) soils in which crop productivity does minimally or not respond to fertilizer – 'poor, less-responsive soils'– due to other constraints besides the nutrients contained in the fertilizer (Path B, Fig. 1). Investment in overall soil fertility rehabilitation through, for example, organic resource management will be required before AE will increase on non-responsive soils (Path C, Fig. 1). A third type of soils, 'rich, less-responsive soils', is not included in the graph since such soils are sufficiently fertile to supply most or all of the nutrients needed by a crop. Inclusion of such soils in Fig. 1 would result in a line with N-AE close to 0 across all ISFM components.

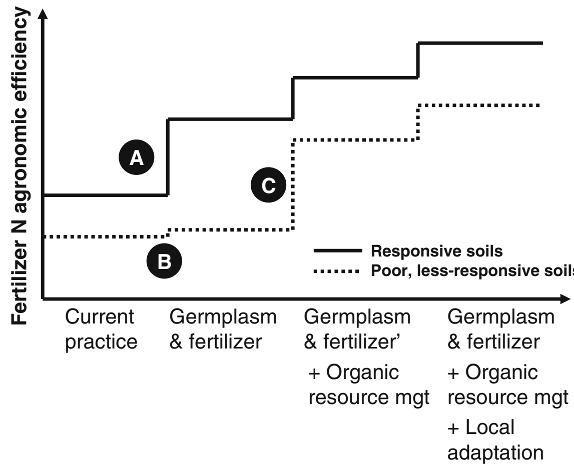


Fig. 1 Conceptual relationship between fertilizer N agronomic efficiency and the implementation of various components of ISFM, culminating in complete ISFM towards the right side of the graph. Soils that are responsive to fertilizer and those that are poor and less-responsive are distinguished. The 'current practice' step assumes the use of the current average fertilizer application rate in SSA of 8 kg fertilizer nutrients ha^{-1}. The meaning of the various steps is explained in detail in the text. Adapted from Vanlauwe et al. (2010)

The application of fertilizer to improved germplasm on responsive soils will boost crop yield and improve the AE relative to current farmer practice in SSA, which is characterized by traditional varieties receiving little nutrient inputs that are often inappropriately managed. Combining organic and mineral inputs has been advocated as a sound management principle for smallholder farming in the tropics since neither of the two inputs is usually available in sufficient quantities and both inputs are needed in the long-term to sustain soil fertility and crop production (Fig. 1) (Vanlauwe et al. 2001a). Mineral inputs are often too expensive for smallholders to be applied at optimal rates and organic inputs applied at rates that are feasible for small-scale farmers seldom release sufficient nutrients for optimum crop yield (Vanlauwe et al. 2001a). Moreover, the combination of the two input types can provide added benefits if managed correctly.

Adjusting for site-specific soil conditions is a last requirement for maximizing AE because of the variability found in farming systems at different scales. Constraints to crop production can vary substantially between different fields within a single farm, creating what is often referred to as 'soil fertility gradients'

(Tittonell et al. 2005; Vanlauwe et al. 2006). Nutrient deficiencies related to soil type can occur at regional levels, but deficiencies related to cropping history and management can differ within short distances on a single farm. Such fertility gradients can have a substantial impact on fertilizer response and adjustment of inputs used along existing soil fertility gradients is one important aspect of local adaptation (Vanlauwe et al. 2006). Often, within-farm gradients of soil fertility are dissected by considering fields close to the homestead, referred to as 'infields', separately from fields furthest away from the homestead, referred to as 'outfields' (Tittonell et al. 2005; Zingore et al. 2007). Adaptation to local conditions also includes accompanying measures that are needed to address constraints that are unlikely to be resolved by fertilizer and/or organic inputs. These measures include the application of lime to acid soils, water harvesting techniques on soils susceptible to crusting, or soil erosion control in hillsides. Again, for poor, non-responsive soils, investment in overall soil fertility rehabilitation will be required before fertilizer AE will be enhanced (Path C, Fig. 1). Zingore et al (2007), for instance, demonstrated that responses to fertilizer on degraded outfields were only obtained after application of 17 Mg $ha^{-1}year^{-1}$ of farmyard manure during 3 consecutive years.

Maize is one of the most important food crops in SSA occupying an average of 13% of all cropped land (www.fao.org). Maize responds well to fertilizer and depending on the country, 8–100% of fertilizer is applied to maize, mostly to hybrid varieties (Wallace and Knausenberger 1997). Notwithstanding the importance of maize, current yield levels are low and far below the agroecological potential of the different maize production areas. On an aggregated level, average maize yields between 2003 and 2007 were 1,576 kg ha^{-1} in West Africa, 1,333 kg ha^{-1} in East Africa, and 2,897 kg ha^{-1} in Southern Africa (http://faostat.fao.org/site/567/default.aspx#ancor). Low maize yield levels are caused by a lack of sufficient nutrient inputs (mainly N, P and K), soil chemical constraints (e.g., soil acidity), soil physical constraints (e.g., soil crusting, plow layers), drought or sub-optimal rainfall conditions, lack of high potential germplasm, and/or pests and diseases (e.g., *Striga hermonthica*, maize streak virus) (Denning et al. 2009; Zingore et al. 2007; Kihara et al. 2010).

Since datasets are lacking that contain information collected through an experimental design containing all the components influencing fertilizer N agronomic efficiency (N-AE) as per Fig. 1, meta-analysis of published data is a useful step towards evaluating whether the conceptual diagram of Fig. 1 has a realistic basis. While narrative reviews provide useful summaries and integration of information for a given discipline, meta-analysis offers more precise and quantitative synthesis of treatment effects by statistically comparing results from multiple studies (Gurevitch and Hedges 1999). This method provides a robust synthesis of results from independent studies in a manner that is both more objective and better statistically defensible (Ainsworth et al. 2007; Hungate et al. 2009). Obviously, publication and research bias cannot be ruled out (Hungate et al. 2009) but is likely less of a problem in our analysis compared to other scientific fields, as non-response to N is rarely seen as a 'failure of technology', whereas a non-response outcome often reduces the chance of publication in other fields. Since in meta-analysis, lots of factors affecting plant growth are not standardized, large standard deviations are expected. As such, this technique is not ideal for developing site-specific fertilizer recommendations but rather in observing general trends and information gaps.

Available information on the N-AE for maize-based systems across SSA was gathered with the objectives of (i) determining the current N-AE levels and their variation under farmer and researcher management for each of the regions of SSA, (ii) evaluating how N-AE is affected by the use of improved maize germplasm, the combined application of fertilizer and organic inputs, and the presence of within-farm soil fertility gradients, and (iii) evaluating the relative importance of above factors in the overall value of N-AE.

Materials and methods

Agronomic efficiency

In the current review, N-AE [kg (kg N)$^{-1}$] is defined as the increase in maize grain yield per unit of fertilizer N applied:

$$\text{N-AE} = (Y_F - Y_C)/F_{appl} \quad (1)$$

where Y_F and Y_C refer to grain yields [kg ha^{-1}] in the treatment where fertilizer N has been applied and in the control plot, respectively, and F_{appl} is the amount of fertilizer N applied [kg Nha^{-1}]. Maximal N-AE leads to a maximal value:cost ratio, an important economic indicator evaluating the investment benefits since both parameters are linearly related for specific input and output prices.

For most papers, the calculation of N-AE was straightforward since yield data and fertilizer N application rates were commonly reported. Only in experimental designs where fertilizer and organic inputs were applied at substitutive (whereby N application rates in the mixed treatment are lower than the sum of those in the sole fertilizer and organic input treatments) instead of additive rates (whereby N application rates in the mixed treatment are the sum of those in the sole fertilizer and organic input treatments), N-AE values were calculated as follows:

$$\text{N-AE} = \left(Y_{Mix} - Y'_{O}\right)/F_{appl} \quad (2)$$

where Y_{Mix} refers to the yield [kg ha^{-1}] in the treatment with both N fertilizer and organic N inputs applied and Y'_O refers to the yield [kg ha^{-1}] in the treatment with only organic N inputs applied at a rate that is equivalent to the rate of organic N inputs applied in the treatment with both N fertilizer and organic N inputs, thereby assuming a linear response to applied organic N input (Vanlauwe et al. 2001b). Y'_O is calculated as:

$$Y'_{O} = Y_C + (Y_O - Y_C)*\left(R'_{O}/R_O\right) \quad (3)$$

where Y_O refers to the yield [kg ha^{-1}] in the treatment with only organic N inputs applied, R'_O to the organic N application rate [kg Nha^{-1}] in the treatment with both N fertilizer and organic N inputs applied, and R_O to the organic N application rate [kg Nha^{-1}] in the treatment with only organic N inputs applied. In case $R'_O=R_O$ then $Y'_O=Y_O$.

Following its definition, N-AE is expected to be constant for the linear part of a typical N fertilizer response curve and then to decrease nonlinearly to zero (Fig. 2a). Similarly, assuming that maize yield in the no-input control plots is a good indicator of soil fertility status, we can expect three regions when plotting yields in the fertilized treatment against control yields: a first region where responses are relatively low – poor, less-responsive fields as described by path B in Fig. 1 (region A in Fig. 2b), a second region where yield increases are maximal – responsive fields as described by path A in Fig. 1 (region B in Fig. 2b), and a third region where fertilizer response is low and gradually decreasing to zero - good, less-responsive fields (region C in Fig. 2b). Consequently, N-AE is expected to increase up to a maximum and to decrease to 0 beyond that maximum (Fig. 2b). In summary, the AE for a particular level of applied N equals the slope of the line joining the control yield (without N application) and the yield obtained at that rate of N applied on the response curve (Fig. 2a). This will be low, independent of management, when the yield obtained with fertilizer falls on the plateau part of the curve. This will occur if either (a) the applied N is high (Fig. 2a) or (b) the plateau starts at low N due to high initial soil

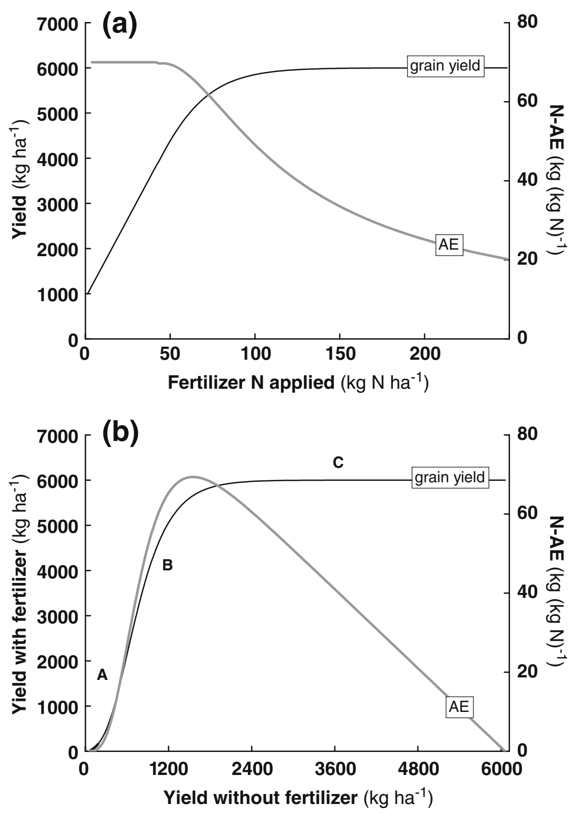


Fig. 2 Conceptual diagrams depicting theoretical relationship between crop yield with fertilizer application and fertilizer N application rate for a single field and the mathematically derived relationship between fertilizer N agronomic efficiency (N-AE) and fertilizer N application rate (**a**), and the theoretical relationship between crop yield with fertilizer application and control yields for a single N application rate, and the mathematically derived relationship between N-AE and control maize yield (**b**). The labels 'A', 'B', and 'C' in Fig b are explained in the text

fertility (Fig. 2b). We used a method to exclude such points from the analysis as they obscure the impact of management which we aim to investigate for typical conditions in SSA (see below).

Literature used and rationale of the paper

The data used in this paper were obtained through specific searches within CABI (www.cabi.org) and other agricultural databases. Only peer-reviewed literature in journals and conference proceedings with information on control yields, yields after N fertilizer application, and fertilizer N rates in maize-based cropping systems in SSA was included in our database. A limited number of PhD theses were also included. Considered papers included data from farm surveys, multi-locational on-farm trials, and replicated on-station trials. A total of 90 peer-reviewed publications fulfilled all the criteria listed above (Annex 1). Furthermore, available data from different sites in Ethiopia, DR Congo, Botswana, Somalia, Rwanda and Tanzania recorded in the Nutrient Response database (Fertibase) of FAO (http://www.fao.org/ag/agl/agll/nrdb/cdrom.jsp?lang=en) were included when they fulfilled our criteria. To assure data independence, as is necessary in meta-analysis (Sileshi et al. 2008), similar data for the same experiment reported in different publications were not repeated and only one set of the data were used. Data from the same study repeated over several seasons were, however, included. Altitude, annual rainfall, and topsoil sand content varied considerably between the three sub-regions (Table 1).

Data analysis methods

Since applying relatively high rates of fertilizer N or applying fertilizer to a relatively fertile soil results per definition in low N-AE values (independent of fertilizer management) and our objectives were to investigate the impact of specific management components on N-AE values under more typical SSA conditions, we removed data points with low N-AE due to high N fertilizer application rates (Fig. 2a) and/or high initial soil fertility conditions (Fig. 2b) from the database before analysis. Ideally, we would estimate N response curves from each study and estimate N-AE from these curves, which would then permit evaluating whether the N application rate is (sub-)optimal or excessive, and whether a particular data point should be removed and retained for analysis. However, the data were rarely sufficiently complete for this. Instead, N-AE values were plotted against control maize yields and fertilizer N application rates for each of the East/Central, West, and Southern African sub-regions and all data in the area under the declining part of the envelope curve was removed. The envelope curve was calculated by classifying the data points over different x-axis intervals (intervals of 500 kg ha^{-1} for the scatter plots against control plot yields and intervals of 20 kg N ha^{-1} for the scatter plots against N application rates) and averaging the N-AE values of the 3 highest points belonging to a specific interval. A constant curve was fitted through the data points covering the linear part with zero slope of the envelope curve and a power function was fitted through the remaining data (see Figs. 3 and 4). Data points with x-axis coordinates exceeding 1.1 times (10% lee way) the x-axis coordinate of the intersection point between the constant and power curve were excluded from further analyses. The 10% lee-way was given to ensure that data points within the error of the calculation procedure were not removed. Beyond these critical x-axis values, the likelihood increased that low AE values were related to excessive N application, or to application of fertilizer on a relatively fertile soil.

The analysis followed the rationale of Fig. 1. First, data were presented on N-AE values obtained by farmers without direct involvement from researchers, followed by N-AE values obtained under researcher-managed conditions. This is followed by an evaluation of the impact of improved open-pollinated and hybrid maize varieties. In a third step, the potential of organic inputs to improve N-AE was evaluated. Organic resources were classified using the Decision Support System for Organic Resource Management (DSS) (Palm et al. 2001) where detailed information on organic input quality was missing from the manuscript. The DSS proposes 4 classes of organic resources, each having specific management options. Class I contains materials with high N (> 25 gkg^{-1}), low soluble polyphenol (< 40 gkg^{-1}), and low lignin (< 150 gkg^{-1}) content and is proposed to be applied directly to the crop. Classes II organic resources have a high N (> 25 gkg^{-1}) and a high polyphenol (> 40 g kg^{-1}) or a high lignin content (> 150 gkg^{-1}), whereas class III organic resources have a low N (< 25 gkg^{-1}), a low polyphenol (< 40 gkg^{-1}), and a low lignin

Table 1 Summary of selected properties related to the various Integrated Soil Fertility Management components considered in the meta-analysis, after removing data with low N fertilizer agronomic efficiency (N-AE) values due to relatively high N application rates or relatively high no-input control yields. The total number of data points retained is 721

Property	Farmer-lead fertilizer management	Researcher-lead fertilizer management	Improved varieties+ researcher-lead fertilizer management	Organic inputs+ researcher-lead fertilizer management	Researcher-lead fertilizer management on infields across soil fertility gradients
Nr cases	24	324	73	272	28
N-AE mean	19	23	34	32	33
N-AE std dev	15	19	23	29	22
N-AE min	-4	−23	−15	−26	6
N-AE max	61	128	83	146	95
Upper quartile	20	30	52	46	39
Median	14	21	37	26	32
Lower quartile	11	9	13	12	20

content (< 150 gkg^{-1}). Resources of Class II and III are proposed to be mixed with either fertilizer or class I organic resources to obtain optimal yields. Class IV organic resources have a low N (< 25 gkg^{-1}) and a high lignin content (> 150 gkg^{-1}) and are advised to be applied as surface mulch. Since the number of Class IV data was very limited, we decided to analyse Class III and Class IV organic inputs together since both classes have a relatively low N content. Manure and compost were considered as a separate class since earlier work showed that such resources do not follow the trends of any of the DSS classes (Vanlauwe et al. 2002a). Since organic inputs themselves contain N, the effect of organic matter application on N-AE was evaluated for different organic N application rates. Lastly, the effect of soil fertility variability between fields within a single farm on N-AE was evaluated using control maize yield as a proxy for soil fertility status. The obtained results were compared with the control yields and N-AE values of the lower and upper quartile control yield ranges of all data with sole N fertilizer application.

All the above comparisons were based on statistical comparisons of trials that contained all the relevant levels of the factors considered, including a treatment with sole N fertilizer application (paired treatments). First, normality of the N-AE data was evaluated and confirmed using Q-Q plots, ensuring that no data transformation was required. The data were then statistically analyzed using the MIXED procedure of SAS (SAS 1992). Fixed factors were the specific factors under consideration (i.e., different varieties, different organic input quality classes, different field types), while the random factor was a unique descriptor for each trial and season. Controls used were (i) fertilizer applied on a local maize variety for Fig. 5 and (ii) sole fertilizer for Fig. 6. Analysis of the influence of within-farm soil fertility gradients was done by including field type as an independent factor in the analysis of variance. Least square means and standard errors of the difference (SED) were calculated using the LSMEANS (least square means) and PDIFF (test of significance for differences) options of the MIXED procedure. Note that due to the unbalanced nature of meta-datasets, mean values can often be substantially different from least square mean values obtained from trials that contained the paired control – effect treatments. For calculation of the standard errors of the difference, least square mean values are required.

Results

N-AE ranges and values retained for further analysis

The constant and power envelope curves intersected at control yields of 5000, 2900, and 2100 kg ha^{-1} for

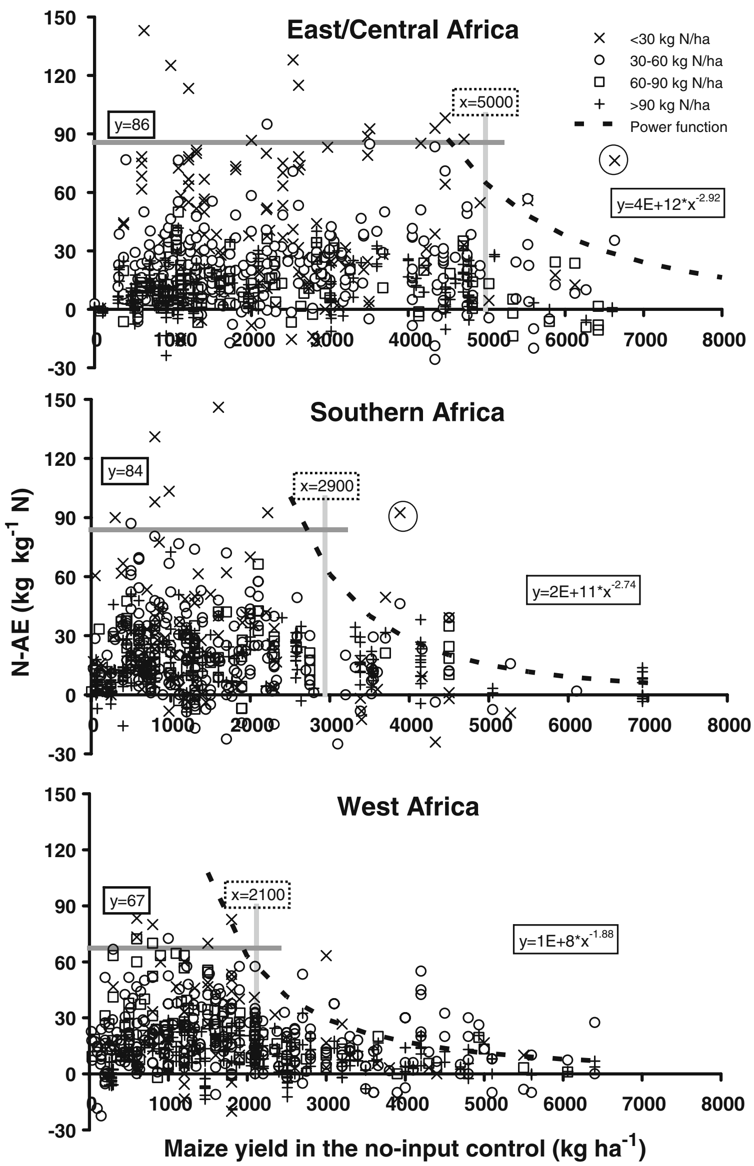


Fig. 3 Agronomic efficiency of fertilizer N (N-AE) at different levels of control yield in East/Central, Southern, and West Africa. The data are presented for 4 different N fertilizer rate ranges. The boundary-line is fitted using the average of 3 highest points (N-AE) for every 500 kg ha^{-1} increments in control yield. Encircled values were excluded from the boundary fitting. Data values larger than the indicated X-value were excluded from the meta-analysis

the East/Central, Southern, and West African datasets, respectively (Fig. 3). Data points with relatively lower N application rates tended to have the highest N-AE values for all regions (Fig. 3). Similarly, when plotting N-AE against N fertilizer application rates, the conceptual trend of Fig. 2a was observed (Fig. 4). The constant and power curves intersected at N application rates of 52, 52, and 96 kg N ha^{-1} for the East/Central, Southern, and West African datasets, respectively. Of the 1927 data points, 721 had control yields and N application rates below the critical values, explained above, and were retained for further analyses.

The retained data covered a wide range of geographic and agro-ecological conditions. For instance, altitudes varied between 50 m above sea level (masl) in the coastal zones of Kenya and Togo, and > 2000 masl in the East-African highlands. Mean annual rainfall in the reported data ranged from <500 mm in Niger and some parts of East and Southern Africa to > 2000 mm in the highlands of East and Central Africa. The study sites covered all predominant soil groups of SSA, i.e. Acrisols, Andosols, Arenosols, Cambisols, Ferralsols, Lixisols, Luvisols and Nitisols (FAO 1991). The organic inputs applied covered mostly organic resource Classes I, II and III, as well as farmyard manure and

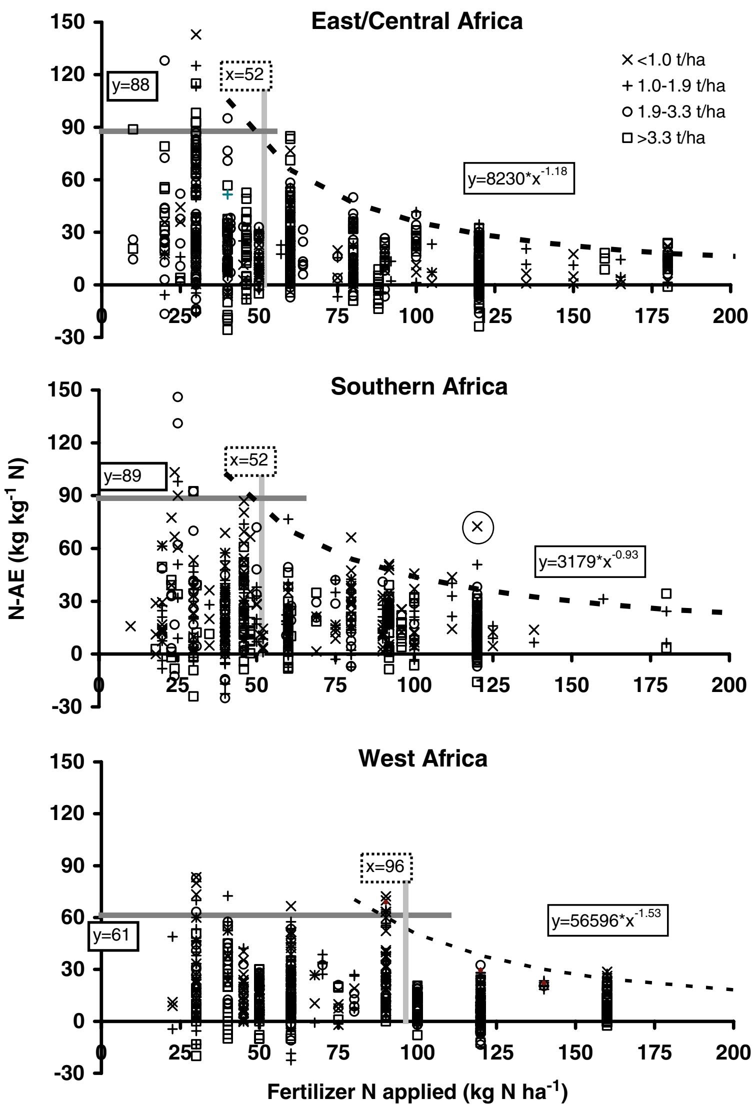


Fig. 4 Agronomic efficiency of fertilizer N (N-AE) at different N application rates in East/Central, Southern, and West Africa. The data are presented for 4 different control yield ranges. The Boundary line is fitted using the average of 3 highest points (N-AE) for every 20 kg N increments in fertilizer applied. Encircled values were excluded from the boundary fitting. Data values larger than the indicated X-value were excluded from the meta-analysis

compost while only a few Class IV organic resources were retained.

N-AE under farmer managed conditions and under researcher management as affected by improved maize germplasm

The average N-AE value for farmer-managed plots (24 cases) was 19 kg (kg N)$^{-1}$ (Table 1). The average N-AE value for researcher-managed plots (324 cases) was 23 kg (kg N)$^{-1}$ (Table 1). With improved hybrid maize varieties, an average N-AE value of 34 kg (kg N)$^{-1}$ (73 cases) was found (Table 1). Least square means calculations from studies that reported N-AE values for both local and improved germplasm showed that improved hybrid maize varieties significantly increased N-AE from 17 to 26 kg (kg N)$^{-1}$, with no differences between local and improved, open-pollinated varieties (OPV) (Fig. 5).

N-AE as affected by mixing fertilizer with organic inputs

Application of organic resources in combination with N fertilizer resulted in an average N-AE value of 32 kg (kg N)$^{-1}$ (272 cases) (Table 1). Following formal statistical testing including all retained datapoints, N-AE values were significantly higher for the

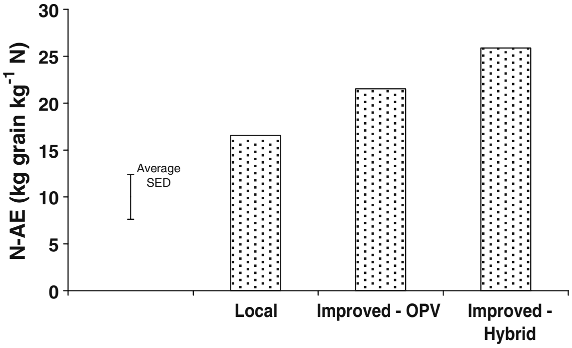
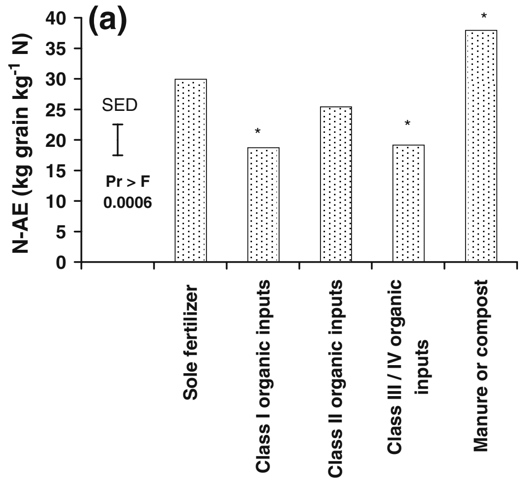


Fig. 5 Agronomic efficiency of fertilizer N (N-AE) for local, improved open-pollinated (OPV), and improved hybrid maize varieties. A total of 11 trial-years were included in the analysis. 'SED' refers to 'Standard Error of the Difference'

treatments where fertilizer was combined with manure or compost [38 kg (kg N)$^{-1}$], but all other organic resources did not significantly affect N-AE values compared to the sole fertilizer treatment [25 kg (kg N)$^{-1}$]. Class I and III/IV organic resources significantly reduced N-AE relative to the sole fertilizer treatment (Fig. 6a). However, when performing the statistical analysis on the data with maximum organic N application rates of 30 or 60 kg N ha^{-1}, organic inputs belonging to Class II and manure/compost had significantly higher N-AE values than the sole fertilizer treatment or the Classes I and III/IV organic inputs (Fig. 6b). At higher organic N application rates, only the treatment with manure/compost gave significantly higher N-AE values than the sole fertilizer treatment (Fig. 6b).

N-AE as affected by targeting within-farm soil fertility gradients

The average N-AE for infields (28 cases) was 33 kg (kg N)$^{-1}$ (Table 1). When analyzing studies where infields and outfields were included in the same study, average no-input control yields were 2300 kg ha^{-1} for the infields and 1400 kg ha^{-1} for the outfields and average N-AE values were 31 kg (kg N)$^{-1}$ for the infields and 17 kg (kg N)$^{-1}$ for the outfields (Figs. 7a and b). When considering the lower and upper quartiles for the no-input control yields from all the sole fertilizer data, thereby assuming that the yield in the no-input control plots is a good indicator for soil fertility status, we observed N-AE values to be consistently higher for the upper [29 kg (kg N)$^{-1}$] than for the lower quartile [19 kg (kg N)$^{-1}$] (Fig. 7c).



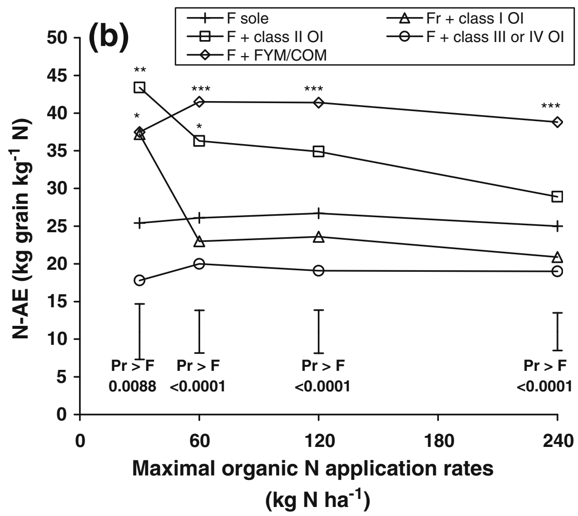


Fig. 6 Agronomic efficiency of fertilizer N (N-AE) as affected by combination with different classes of organic inputs (Classes I, II, III+IV, and manure+compost), including all retained data-points (114 trial-years) (a) and the same graph for organic N application rates≤30 kg N ha^{-1} (30 trial-years), ≤ 60 kg N ha^{-1} (58 trial-years), ≤ 120 kg N ha^{-1} (69 trial-years), or ≤ 240 kg N ha^{-1} (81 trial-years) (b). Error bars are average Standard Errors of the Difference. The symbols '*', '**', and '***' indicate a significant difference with the sole fertilizer treatment at the 0.1, 1, and 5% level. In the legend, 'F', 'OI', 'FYM', and 'COM' refer to fertilizer, organic inputs, manure, and compost, respectively

Discussion

Observed N-AE values were low under farmer management conditions but the application of specific ISFM components resulted in substantial increases in N-AE. The average N-AE value observed under farmer management in this meta-analysis (19 kg

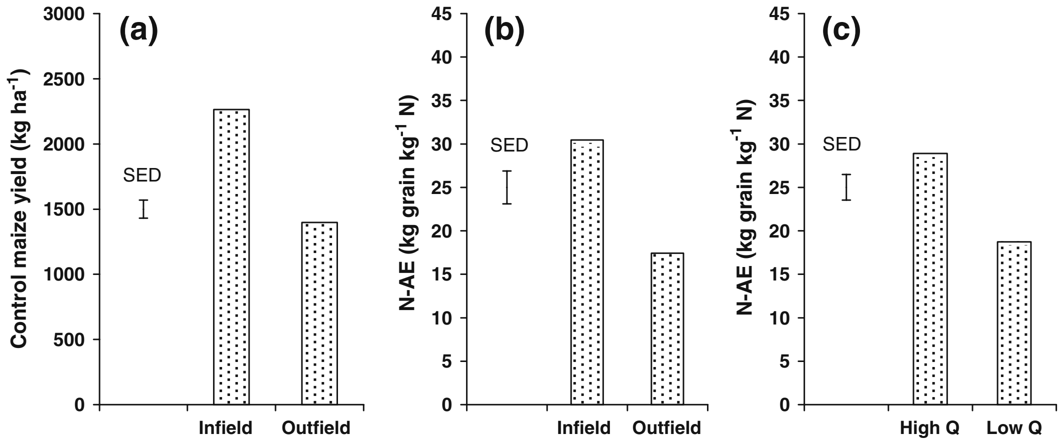


Fig. 7 Maize control yields for paired comparisons between infields and outfields within single studies (**a**), N fertilizer agronomic efficiency (N-AE) for the paired comparisons (**b**), and N-AE of fields with the maize control yields belonging to the lower (Low Q) and upper quartile ranges (High Q) across the three regions. A total of 6 trial-years were included in the analysis that generated Figs 7a and b. 'SED' refers to 'Standard Error of the Difference'

$(kg\ N)^{-1}$) was close to the average N-AE [14 kg $(kg\ N)^{-1}$] obtained in the Malawi fertilizer subsidy program (Chinsinga 2008). Malawi became a net food exporter through the widespread deployment of subsidized seeds and fertilizer, but the aggregated N-AE was relatively low, indicating the large potential for ISFM as it could at least double N-AE values with all consequent economic benefits to smallholder farmers.

Agronomic efficiency of researcher-managed and farmer-managed fertilizer equaled 23 and 19 kg $(kg\ N)^{-1}$, respectively. Although formal statistical analysis was not possible due to absence of paired data in the database, these values were rather similar. Appropriate agronomic and fertilizer management practices, including maize planting densities, timely planting and weeding (Tittonell et al. 2007), and split fertilizer application (Piha 1993) can substantially enhance N-AE. Bationo et al. (1997) observed an important effect of good agronomy and fertilizer management (descriptively assessed using planting density, date of planting and time of phosphorus application, etc) on maize grain yield in Mali. The lack of differences in N-AE between farmer-managed and researcher-managed activities and the overall low value for N-AE under researcher-managed conditions in our meta-analysis is probably related to the inclusion of less- to non-responsive, degraded soils in the overall dataset (Fig. 1). These soils are different from those fertile, non-responsive soils, excluded from the current analysis, as explained above.

The inclusion of improved hybrid maize germplasm increased N-AE from 17 to 26 kg $(kg\ N)^{-1}$ while improved OPVs showed similar N-AE values as the local materials. It has previously been observed that hybrid maize results in greater N-AE than local maize cultivars in Zambia (18 vs 11 kg $(kg\ N)^{-1}$) or Malawi (52 vs 38 kg $(kg\ N)^{-1}$) (Heisey and Mwangi 1996). Furthermore, Pixley and Banzinger (2001) reported yield enhancements of 18% of 4 elite hybrid varieties over 10 elite OPV varieties. The use of recycled hybrid seed resulted in a yield loss of 32% for hybrids and 5% for OPVs (Pixley and Banzinger 2001). Although hybrid varieties can result in higher N-AE values, farmers often prefer OPV maize since seeds from the latter can be recycled while seeds of the former need to be purchased each season.

Mixing fertilizer with organic resources had a substantial impact on N-AE but only with manure/compost or Class II organic inputs. Class II organic inputs and manure/compost substantially increased N-AE most likely through the alleviation of other crop growth constraints besides N. Class II organic inputs have a relatively high N content but also contain a considerable amount of soluble polyphenols that can create stable complexes with protein-N (Palm et al. 2001). As such, their decomposition is usually delayed and the potential of such resources to alleviate other constraints to maize growth besides N is thus higher compared to Class I or Class III residues. Manure and compost are unlikely to result in lasting N immobilization since these materials have gone through a decomposition phase before application to the maize. However, other constraints alleviated could be related to improved soil moisture conditions, weed suppression, or better soil physico-chemical conditions (Vanlauwe et al., 2001a).

Previously, it has been observed that Class I materials decompose rapidly and behave, in essence, as fertilizer in terms of their N availability (Palm et al. 2001; Vanlauwe et al. 2002a). Consequently, adding high rates of Class I organic resources increases the amount of N with high fertilizer equivalency value, quickly exceeding the cut-off N rates (see Fig. 4). The data presented in Fig. 6b indicated that this appeared to happen already at organic N rates of 60 kg N ha^{-1}. When evaluating the impact of Class I organic resources on N-AE, it is thus important to consider that the N contained in these organic resources also contributes to the short term N supply and can thus result in low N-AE values if the total N application rate is high. Class III organic resources of which the decomposition process is not delayed by the presence of chemically recalcitrant components but by lack of N, can immobilize N and thus compete with the crops for N (Vanlauwe et al. 2002b; Gentile et al. 2008), resulting in reduced N-AE values. However, this immobilization is temporary and in the medium or long-term, Class III organic inputs could result in substantial improvements in N-AE.

Targeting fertilizer to different fields within a single farm was also observed to significantly affect N-AE: N-AE values in infields were almost twice as large as N-AE values in outfields. Earlier, Tittonell et al. (2008) distinguished three broad classes of fields: (i) fertile, less-responsive fields, (ii) responsive fields in which a strong response to fertilizers is found, and (iii) poor, less-responsive fields. A good proxy for soil fertility status is often the soil organic matter (SOM) content as SOM contributes positively to soil properties or processes fostering crop growth, such as cation exchange capacity, soil moisture and aeration, or nutrient stocks. On land where these constraints limit crop growth, a higher SOM content may enhance the demand by the crop for N and consequently increase the N-AE. On the other hand, SOM also releases available N that could be hypothesized to be better synchronized with the demand for N by the plant than fertilizer N. If the N release from the SOM meets a large proportion of the crop's N requirement, then N-AE will be reduced. Evidence from Western Kenya shows that the N-AE for fertile soils is less than that for less intensively managed outfields (Vanlauwe et al. 2006). Heisey and Mwangi (1996) also observed that the N-AE in depleted sites was twice as high as in sites of high fertility. In this analysis, after removal of data obtained on relatively fertile fields, infields appear to be equivalent to responsive fields and outfields equivalent to poor, less-responsive fields. Interestingly, similar trends were observed when looking at the lower and upper control yield quartiles for the overall sole fertilizer database component, although the N-AE differences were less pronounced probably because of the unbalanced nature and the lack of consistent management between field types for the sole fertilizer database.

When looking across the various ISFM components, the following order can be observed in terms of average N-AE values: local management (19 kg (kg N)$^{-1}$) <= fertilizer+Class I or III organic inputs (20 kg (kg N)$^{-1}$) <= fertilizer sole (23 kg (kg N)$^{-1}$)< infields (33 kg (kg N)$^{-1}$) <= improved germplasm (36 kg (kg N)$^{-1}$) <= fertilizer+Class II organic inputs or manure/compost (39 kg (kg N)$^{-1}$). This demonstrates that the basic principles underlying Fig. 1 are well-founded and that the application of ISFM principles can substantially improve N-AE. However, evidence for the different 'steps' is fragmented and derived from different cropping systems and agro-ecological zones. A further concerted effort with a standardized multi-locational factorial design, encompassing all ISFM components conceptualized in Fig. 1, laid out over existing within and between-farm soil fertility gradients is needed to further determine if complete ISFM can lift N-AE close to its maximum.

In the current database, 12% of the retained N-AE values were below 5 kg (kg N)$^{-1}$, with some even negative, while 7% were above 70 kg (kg N)$^{-1}$, with 8 values exceeding 100 kg (kg N)$^{-1}$. Low N-AE values could be obtained in soils where physical, biological, or chemical degradation restrains responses to fertilizer N, referred to as 'poor, less-responsive soils' by Vanlauwe et al. (2010). Negative N-AE values are difficult to explain unless there are mechanisms whereby fertilizer application reduces the relative availability of native soil N compared with the no-input control soil, e.g., when fertilizer scorches the seed when it is placed too close to the seed under relatively dry conditions. On the other extreme, the average maximal N-AE values obtained [61–88 kg (kg N)$^{-1}$] are close to the theoretical maximum dilution (70 kg (kg N)$^{-1}$), as determined by Janssen et al. (1990) through their Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) work. The QUEFTS equation for maximum dilution of N in maize is: YND (kg ha^{-1}) as 70 * (UN-5) kg Nha^{-1} with YND referring to the maize yield under maximum N dilution and UN referring to the total maize N uptake. Assuming a theoretical 100% recovery of applied fertilizer N, we would thus have a maximal N-AE of 70 kg (kg N)$^{-1}$. This empirical equation indicates that N-AE values much larger than 70 kg (kg N)$^{-1}$ are unlikely unless there are important positive interactions between the applied fertilizer N and the soil N supply capacity. Such positive interactions between applied fertilizer N and the native soil N supply have been observed (Jenkinson et al. 1985; Ladha et al. 2005).

The range and spread of the N-AE values differed widely between the considered regions (Figs. 3 and 4). While N-AE values remained relatively higher for high control yields in East/Central Africa, compared to the other two regions, N-AE values remained relatively high under high fertilizer N application rates in West Africa compared to the other two regions (Figs. 3 and 4). These trends are likely the result of different yield potentials and inherent soil fertility conditions in the various regions. Soils in West and Southern Africa were generally poorer and more prone to N losses than those in East/Central Africa, as indicated by their topsoil sand content (Table 2) whereas yield potentials appeared to be higher in East/Central and Southern Africa compared with West-Africa. If the above is correct, then it is expected that cut-off yields (Fig. 3) for East/Central Africa are higher than for Southern and West Africa (Fig. 3) because the East/Central African region has a higher yield potential than the West African region and more annual rainfall than the Southern African region (Table 2). It is also expected that cut-off N rates are similar for East/Central and Southern Africa (Fig. 4) because soils and soil N supply rates are most likely better in East/Central Africa. Cut-off N rates of West Africa are expected to be higher than those of Southern Africa because of the higher rainfall. When explaining the above trends, one should also consider the possibility that the maize germplasm used within a certain region can have substantially different N conversion efficiencies than the germplasm used in other regions.

Average N-AE values for SSA, as reported in this paper, are comparable to N-AE values obtained in other regions of the world. For example, in the USA, N-AE was up to 31 kg (kg N)$^{-1}$ for a fertilizer application rate of 144 kg N ha^{-1}. In most cases, N-AE values of 10–30 kg (kg N)$^{-1}$ were achieved and values over 25 kg (kg N)$^{-1}$ were obtained in well-managed systems, at low levels of N use, or at low soil N supply (Dobermann and Cassman 2004). Johnson and Raun (2003) observed N-AE of 27 kg (kg N)$^{-1}$ (fertilizer application rate of 90 kg N ha^{-1}) with irrigated maize in a 15-year study in the USA while rain-fed maize had N-AE values of 18 and 11 kg (kg N)$^{-1}$ for fertilizer application rates of 56 and 112 kg N ha^{-1}, respectively (Uribelarrea et al. 2009). xIn India, N-AE of 19.5 kg (kg N)$^{-1}$ was observed for sole N applied in Prasat India (Roberts 2008). In northwest Pakistan, N-AE was 28 kg (kg N)$^{-1}$ at an application rate of 60 kg N ha^{-1} but decreased to 23 and 19 kg (kg N)$^{-1}$ at application rates of 120 and 180 kg N ha^{-1}, respectively; N-AE values increased when the number of split applications was increased (Amanullah and Alkas 2009).

Table 2 Selected biophysical average characteristics of the target regions. 'SED' refers to Standard Error of the Difference

Region	Altitude (masl)	Annual rainfall (mm)	Topsoil sand content (%)
East/Central Africa	1375	1172	37
Southern Africa	1248	815	75
West Africa	412	1248	69
SED	153	112	7
Pr>F	< 0.0001	0.0032	0.0021

Conclusions

Meta-analysis was used to evaluate the impact of the various components embedded in the revised ISFM definition on N-AE for maize-based systems in sub-Saharan Africa. Inclusion of improved maize germplasm, combining organic inputs of Classes II or manure/compost in combination with fertilizer, and targeting fertilizer to responsive infields was shown to substantially enhance N-AE compared with N-AE values obtained under farmer management. Consequently, the basic principles underlying ISFM are well-founded and good entry points for substantial improvements in N-AE. However, due to the high levels of variation inherent to meta-analysis and the lack of experimental designs that include all components embedded in ISFM, a consistent, multi-locational design is required, involving all ISFM components in an unbiased way, to obtain the optimal N-AE adapted to specific biophysical conditions across agricultural landscapes and to develop site-specific recommendations for fertilizer management.

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Annex 1

Papers included in this study. Themes addressed are: (1) local, farmer-lead fertilizer management, (2) good, researcher-lead fertilizer mgt, (3) improved varieties, (4) fertilizer+organic inputs, and (5) within-farm soil fertility gradients.

Authors	Source	Country	Data points	Themes
Abdulahi et al. 2006	Karsetsart J (nat sci) 40:604–615	Ethiopia	12	2
Akinnifesi et al. 2007	Plant Soil 294: 203–207	Malawi	48	4
Akintoye et al. 1999	Field Crops Res 60: 189–199	Nigeria	18	2
Akulumuka et al. 1996	CIMMYT 5th Maize Conf	Tanzania	2	2
Azeez et al. 2006	Soil Tillage Res 91: 181–185	Nigeria	11	3
Bado et al. 2004	Bationo A (ed) 2004 p77–88	Burkina Faso	26	2
Barron and Okwach 2005	Agric Water Manage 74: 1–21	Kenya	16	3
Chikowo et al. 2003b	PhD Thesis	Zimbabwe	2	4
Chikowo et al. 2004	Plant Soil 262: 303–315	Zimbabwe	6	4
Chikoye et al. 2008	Weed Science 56: 424–433	Nigeria	36	3
Chilimba et al. 2004	CIMMYT Working Paper No. 11	Malawi	22	4
Chivenge et al. 2009	Agron J. 101: 1266–1275	Kenya	110	4
Delve 2004	Bationo A (ed) 2004 p127–136	Uganda	3	4
Dimes et al. 2001	Friesen D.K. and Palmer, A.F.E. (eds). 2001. p 452–456	Malawi, Zimbabwe	8	2
Elisaba et al. 2000	African Crop Sci J 8: 403–410	Ethiopia	27	4
FERTIBASE	FAO 2009 (www.fao.org)	sub-Saharan Africa	217	2
Fofana et al. 2005	Nutr Cycl Agroecosyst 71: 227–237	Togo	96	4
Franke et al. 2008	Nutr Cycl Agroecosyst 82:117–135	Nigeria	81	2, 4
Gigou et al. 2002	Vanlauwe et al.(eds) 2002. p 199–208	Cote d'Ivoire	78	4
Gikonyo and Smithson 2004	Bationo A (ed). 2004 p137–150	Kenya	3	4
Gladwin et al. 2001	Food Policy 26:177–207	Malawi	4	1
Goma 2003	Soil Fert. Mgt Africa, CIAT, p187–281	Zambia	2	2
Horst et al. 1994	Plant Soil 160: 171–183	Ghana	2	2
Ikerra et al. 1998	CIMMYT 6th Maize Conf Proc	Malawi	4	2
Iwuafor et al. 2002	Vanlauwe et al.(eds). 2002. p 185–198	Nigeria, Benin	8	4

Jeramanya et al. 2007	African J Biotechn 6 (13): 1503–1508	Zimbabwe	6	2
Kaizzi et al. 2006	Agr Syst 88: 44–60	Uganda	16	5
Kamara et al. 2002	Tropentag 2002	Nigeria	22	3
Kayode and Agboola 1981	Fert Res 2:177–191	Nigeria	24	2
Kihanda et al. 1998	CIMMYT 6th Maize Conf Proc, 250–252	Kenya	4	4
Kihara et al. 2010	Exp agric 46:1–18	Kenya	24	2
Kim et al. 2007	Trop Sci 47 (4): 149–158	Nigeria	24	3
Kimani and Lekasi 2004	Bationo A (ed) 2004 p187–197	Kenya	6	4
Kimani et al. 2007	Bationo et al. (eds) 2007. p353–358	Kenya	14	4
Kimaro et al. 2009	Agric Ecosyst Environ 134: 115–125	Tanzania	16	4
Kimetu et al. 2004	Nutr Cycl Agroecosyst 68: 127–135	Kenya	12	4
Kiwia et al. 2009	Agrofor Syst 76: 455–465	Kenya	2	2
Kumwenda et al. 1998	CIMMYT Soil Fert Mal & Zim	Malawi	16	4
Kwesiga et al. 1999	Agrofor Syst 47: 49–66	Zambia	5	2
Lungu and Dynoodt 2008	African J Food Agric Nutr Dev 8:63–76	Zambia	12	2
Kakumba et al. 2001	SADC/ICRAF 14th S Africa Proc	Malawi	8	4
Mapiki et al. 1993	Aria Agrir. Srunrl. Sect. B. Soil orid Plurir Sri. 1993: 43, 231–237	Zambia	3	2
Mariki et al. 1996	CIMMYT 5th Maize Conf	Tanzania	6	4
Minde et al. 2008	ReSAKSS Working Paper No. 13	Kenya, Zambia	10	1
Mochoge and Onwonga 1998	CIMMYT 6th Maize Conf Proc	Kenya	17	2
Mtambanengwe and Mapfumo 2006	Plant Soil 28: 173–191	Zimbabwe	4	2
Mtambanengwe et al. 2006	Nutr Cycl Agroecosyst 76: 271–284	Zimbabwe	110	4
Mugendi et al. 1999	Agrofor Syst 46: 30–50	Kenya	3	4
Mugwe et al. 2007	Afr Crop Sci J 15(3):111–126	Kenya	47	4
Mugwe et al. 2009	Exp agric 45: 47–59	Kenya	4	2
Muhr et al. 2002	Field Crops Res 78: 197–209	Nigeria	4	2
Mumera and Below 1993	Crop sci 33: 758–763	Kenya	6	2
Murwira et al. 1998	CIMMYT Soil Fert Mal & Zim	Zimbabwe	48	4
Mugwira and Murwira, 1997	CIMMYT Soil Fert Net working paper no. 2, 18 pp	Zimbabwe	4	4
Mushayi, et al. 1999	CIMMYT 6th Maize Conf Proc	Zimbabwe	4	2
Nhamo 2002	MPhil thesis	Zimbabwe	81	4
Nyadzi et al. 2006	Agric Ecosyst Environ 116: 93–103	Tanzania	2	4
Nyamangara et al. 2003	African Crop Sci J 11: 289–300	Zimbabwe	12	4
Nyathi et al. 1995	African Crop Sci J. 3: 451–456	Zimbabwe	3	4
Nziguheba et al. 2004	Bationo A (ed) 2004 p329–345	Kenya	20	4
Nziguheba et al. 2009	Plant Soil 314:143–157	Benin, Nigeria	20	4
Oikeh et al. 1999	Field Crops Res 62: 1–13	Nigeria	2	2
Oikeh et al. 2007	African J Agric Res 2 (3): 112–118	Nigeria	2	2
Ojiem 2006	PhD Thesis	Kenya	12	5
Okalebo et al. 1999	Afr Crop Sci J 7(4): 423–431	Kenya	27	4
Onyango et al 1998	CIMMYT 6th Maize Conf Proc	Kenya	25	4
Pandey et al. 2000	Agric Water Manage 46: 1–13	Niger	24	2

Phiri et al.1999	Agrofor Syst 47: 153–162, 1999	Malawi	3	2
Saka et al. 2007	Malawi J Agr Sci 3(1): 49–57	Malawi	3	2
Sakala et al. 2001	DARS Annual Proc	Malawi	2	2
Sakala et al. 2004	Bationo A (ed) 2004 p373–384	Malawi	28	2, 3
Sallah et al. 2009	J Appl Biosci 20: 1194–1202	Rwanda	6	2
Shiluli et al. 2003	Afr Crop Sci J 11(3): 181–187	Kenya	8	2
Sigunga et al. 2002	Nutr Cycl Agroecosyst 62: 263–275	Kenya	10	2
Snapp et al. 1998	Agric Ecosyst Environ 71: 185–200	Zimbabwe	2	4
Swift et al. 1994	Roth Long-term Exp Proc, CABI, 229–251	Kenya	29	4
Tabi et al. 2008	Nutr Cycl Agroecosyst 80: 161–172	Nigeria	8	2
Tabu 2001	PhD Thesis	Kenya	12	5
Tabu et al. 2006	Agron J 5(2): 191–195	Kenya	18	5
Teklay et al. 2006	Nutr Cycl Agroecosyst 75:163–173	Ethiopia	5	4
Vanlauwe et al., 2001	Agron J 93:1191–1199	Cote D'Ivoire, Benin, Togo, Nigeria	16	2
Vanlauwe et al. 2005	Plant Soil 273: 337–354	Nigeria	40	4
Wiyo and Feyen 1999	Agric Water Manage 41: 21–39	Malawi	16	1
Woldetsadik et al. 2005a	Kasetsart J Nat Sci 39:1–11	Ethiopia	6	2
Woldetsadik et al. 2005b	Kasetsart J Nat Sci 39:338–349	Ethiopia	6	2
Wopereis et al. 2006	Field Crops Res 96: 355–362	Togo	12	5
Workayehu and Kena 1998	CIMMYT 6th Maize Conf Proc	Ethiopia	27	4
Yeboah et al. 2007	PhD Thesis	Ghana	33	4
Yusuf et al. 2009	Nutr Cycl Agroecosyst 84: 129–139	Nigeria	6	2
Zingore et al. 2007	Field Crops Res 101: 296–305	Zimbabwe	56	5

References

Abuja Fertilizer Summit (2006) Abuja Declaration on Fertilizer for African Green Revolution, African Union Special Summit of the Heads of State and Government, Abuja, Nigeria

Amanullah, Alkas LK (2009). Partial factor productivity, agronomic efficiency, and economic analyses of maize in wheat-maize cropping system in Pakistan. No. 46747. Southern Agricultural Economics Association Annual Meetings, Atlanta, Georgia, January31- February 3, 2009, 26 pp.

Ainsworth EA, Rosenburg MS, Wang X (2007) Meta-analysis: the past, present and future. New Phytol 176:752–745

Bationo A, Ayuk E, Ballo D, Kon´e M (1997) Agronomic and economic evaluation of Tilemsi phosphate rock in different agroecological zones of Mali. Nutr Cycl Agroecosyst 48:179–189

Chinsinga B (2008) Reclaiming Policy Space: Lessons from Malawi's 2005/2006 Fertilizer Subsidy Programme Future Agricultures. Institute of Development Studies, Brighton, UK

Denning G, Kabambe P, Sanchez P, Malik A, Flor R, Harawa R, Nkhoma P, Zamba C, Banda C, Magombo C, Keating M, Wangila J, Sachs J (2009) Input Subsidies to Improve Smallholder Maize Productivity in Malawi: Toward an African Green Revolution. PLOS Biol 7(1):e1000023

Dobermann A, Cassman KG (2004) Environmental dimensions of fertilizer nitrogen: what can be done to increase nitrogen use efficiency and ensure global food security? In: Mosier AR, Syers JK, Freney JR (eds) Agriculture and the nitrogen cycle: Assessing the impacts of fertilizer use on food production and the environment. Island Press, Washignton DC, USA, pp 261–278

FAO (1991) World Soil Resources: An Explanatory Note on the FAO World Soil Resources Map at 1:25, 000, 000 Scale. Food and Agriculture Organisation of the United Nations, Rome, Italy

Gentile R, Vanlauwe B, Chivenge P, Six J (2008) Interactive effects from combining fertilizer and organic residue inputs on nitrogen transformations. Soil Biol Biochem 40:2375–2384

Gurevitch J, Hedges LV (1999) Statistical issues in ecological meta-analyses. Ecology 80:1142–1149

Heisey P W, Mwangi W (1996) Fertilizer use and maize production in sub-Saharan Africa. CIMMYT economic working paper 96-01. Mexico, DF, CIMMYT

Hungate BA, van Groenigen KJ, Six J, Jastrow JD, Luo Y, de Graaff MA, van Kessel C, Osenberg CW (2009) Assessing the effect of elevated carbon dioxide on soil carbon: a comparison of four meta-analyses. Global Change Biol 15:2020–2034

Janssen BH, Guiking FCT, van der Eijk D, Smaling EMA, Wolf J, van Reuler H (1990) A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46:299–318

Jenkinson DS, Fox RH, Rayner JH (1985) Interactions between fertilizer nitrogen and soil nitrogen – the so-called 'priming' effect. J Soil Sc 36:425–444

Johnson GV, Raun WR (2003) Nitrogen response index as a guide to fertilizer management. J Plant Nutr 26: 249–262

Kihara J, Vanlauwe B, Waswa B, Kimetu JM, Chianu J, Bationo A (2010) Strategic phosphorus application in legume-cereal rotations increases land productivity and profitability in western Kenya. Exp Agric 46:35–52

Ladha JK, Pathak H, Krupnik TJ, Six J, van Kessel C (2005) Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. Adv Agr 87:85–156

Palm CA, Gachengo CN, Delve RJ, Cadisch G, Giller KE (2001) Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric Ecosyst Environ 83:27–42

Piha MI (1993) Optimizing fertilizer use and practical rainfall capture in a semi-arid environment with variable rainfall. Exp Agric 29:405–415

Pixley K, Banziger M (2001) Open-pollinated maize varieties: A backward step or valuable option for farmers? Seventh Eastern and Southern Africa Regional Maize Conference, 11–15th February 2001, pp. 22–28

Roberts TL (2008) Improving Nutrient Use Efficiency. Turk J Agric For 32:177–182

SAS 1992. The MIXED procedure. SAS Technical Report P-229: SAS/STAT Software: Changes and Enhancements. SAS Institute Inc., Cary, NC, USA

Sileshi G, Akinnifesi FK, Ajayi OC, Place F (2008) Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. Plant Soil 307:1–19

Tittonell P, Vanlauwe B, Leffelaar PA, Shepherd KD, Giller KE (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya. II. Within farm variability in resource allocation, nutrient flows and soil fertility status. Agric Ecosyst Environ 110:166–184

Tittonell P, Vanlauwe B, de Ridder N, Giller KE (2007) Heterogeneity of crop productivity and resource use efficiency within smallholder African farms: soil fertility gradients or management intensity gradients? Agr Syst 94:376–390

Tittonell P, Vanlauwe B, Corbeels M, Giller KE (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313:19–37

Uribelarrea M, Crafts-Brandner SJ, Below FE (2009) Phsiological N response of field-grown maize hybrids (Zea mays L.) with divergent yield potential and grain protein concentration. Plant Soil 316:151–160

Vanlauwe B, Wendt J, Diels J (2001a) Combined application of organic matter and fertilizer. In: Tian G, Ishida F, Keatinge JDH (eds) Sustaining Soil Fertility in West-Africa, SSSA Special Publication Number 58. Madison, USA, pp 247–280

Vanlauwe B, Aihou K, Aman S, Iwuafor ENO, Tossah BK, Diels J, Sanginga N, Merckx R, Deckers S (2001b) Maize yield as affected by organic inputs and urea in the West-African moist savanna. Agron J 93:1191–1199

Vanlauwe B, Palm CA, Murwira HK, Merckx R (2002a) Organic resource management in sub-Saharan Africa: validation of a residue quality-driven decision support system. Agronomie 22:839–846

Vanlauwe B, Diels J, Aihou K, Iwuafor ENO, Lyasse O, Sanginga N, Merckx R (2002b) Direct interactions between N fertilizer and organic matter: evidence from trials with 15 N labelled fertilizer. In: Vanlauwe B, Diels J, Sanginga N, Merckx R (eds) Integrated Plant Nutrient Management in sub-Saharan Africa: From Concept to Practice. CABI, Wallingford, UK, pp 173–184

Vanlauwe B, Tittonell P, Mukalama J (2006) Within-farm soil fertility gradients affect response of maize to fertilizer application in western Kenya. Nutr Cycl Agroecosyst 76:171–182

Vanlauwe B, Bationo A, Chianu J, Giller KE, Merckx R, Mokwunye U, Ohiokpehai O, Pypers P, Tabo R, Shepherd K, Smaling E, Woomer PL, Sanginga N (2010) Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. Outl on Agric 39:17–24

Wallace MB, Knausenberger WJ (1997) Inorganic fertilizer use in Africa: Environmental and Economic dimensions

Zingore S, Murwira HK, Delve RJ, Giller KE (2007) Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. Field Crops Res 101:296–305